

Real-time In-Flight Strain and Deflection Monitoring with Fiber Optic Sensors



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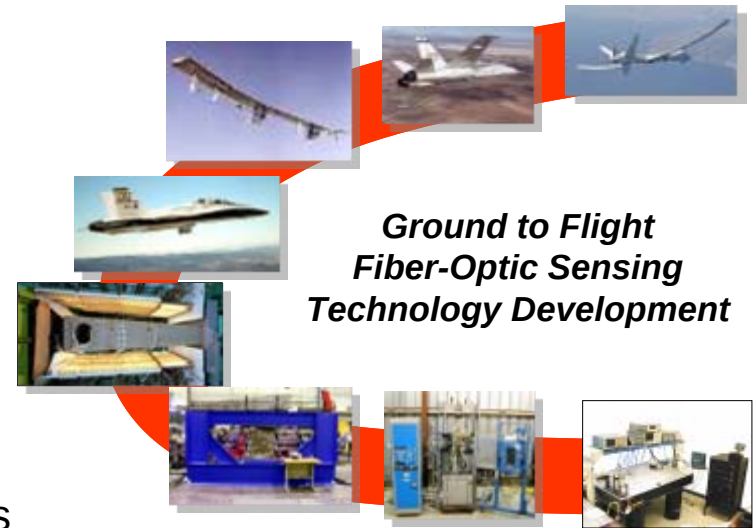
Space Sensors and Measurements Techniques Workshop

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Background

- Dryden's Aerostructures Branch initiated fiber-optic instrumentation development effort in the mid-90's
 - Dryden effort focused on atmospheric flight applications of Langley patented OTDR demodulation technique
- Dryden collaborated on X-33 IVHM Risk Reduction Experiment on F/A-18 System Research Aircraft
 - Focused on validating Lockheed Sanders FO VHM system
 - Flew fiber optic instrumented flight test fixture with limited success due to problem with laser
 - Lockheed Sanders system limited to 1 sample every 30 seconds
- Dryden initiated a program to develop a more robust / higher sample rate fiber optic system suitable for monitoring aircraft structures in flight



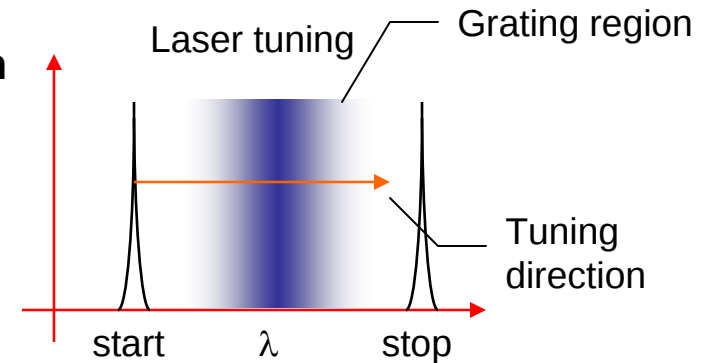
X-33 IVHM Risk
Reduction Experiment



Fiber Optic System Operation Overview

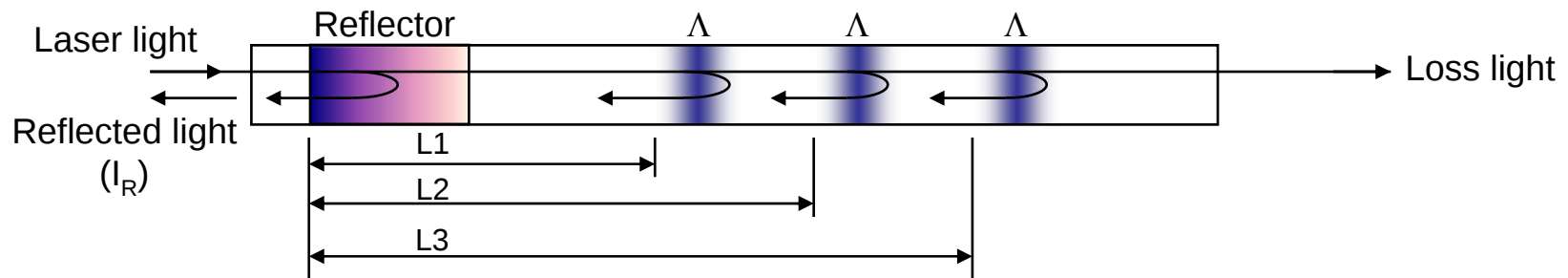
Fiber Optic Sensing with Fiber Bragg Gratings

- Immune to electromagnetic / radio-frequency interference and radiation
- Lightweight fiber-optic sensing approach having the potential of embedment into structures
- Multiplex 100s of sensors onto one optical fiber
- Fiber gratings are written at the same wavelength
- Typical gage lengths from 0.1mm to 100mm
- Uses a narrowband wavelength tunable laser source to interrogate sensors
- Typically easier to install than conventional strain sensors



$$I_R = \sum_i R_i \cos(k2nL_i) \quad k = \frac{2\pi}{\lambda}$$

R_i – spectrum of i^{th} grating
 n – effective index
 L – path difference
 k – wavenumber

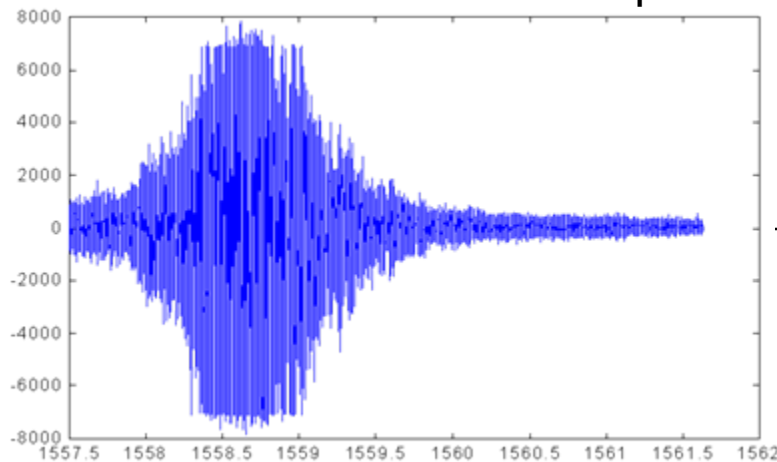


Fiber Optic System Operation Overview

- Fourier transforms (both forward and inverse) are used to discriminate between gratings
- The Fourier transform separates the I_R waveform into sinusoids of different frequency which sum to the original waveform

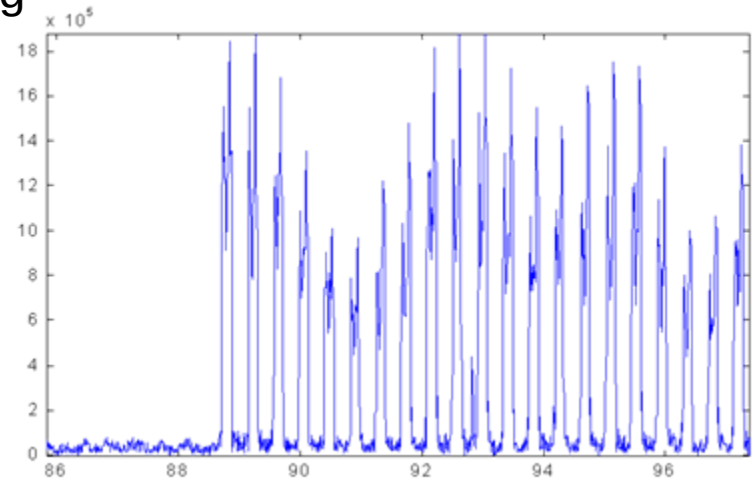
	FFT	iFFT
Traditional	Time(T) > Frequency(F)	Frequency(F) > Time(T)
Optical	Wavelength(λ) > Length(L)	Length(L) > Wavelength(λ)

Spectral Mapping



Wavelength(λ) domain

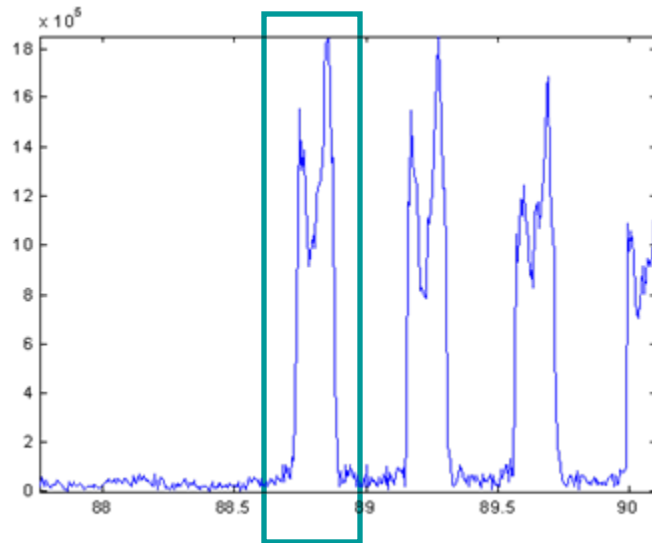
FFT



Length(L) domain

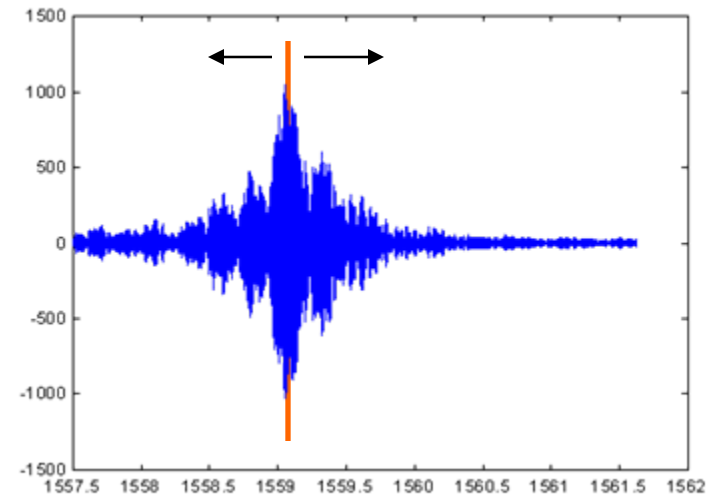
Fiber Optic System Operation Overview

- By bandpass filtering around a specific frequency (grating location) within the length domain and performing an iFFT, the spectrum of each grating can be independently measured and strain inferred (FM radio)



Length(L) domain (inches)

iFFT
→



Wavelength(λ) domain

- Using a centroid function the center wavelength can be resolved
- The wavelength change is proportional to the induced strain

$$\frac{\Delta\lambda}{\lambda} = K\varepsilon$$

K – proportionality constant (0.7-0.8)

Motivation – Helios Mishap



Helios wing dihedral on takeoff



In-flight breakup

Helios Mishap Report – Lessons Learned

- Measurement of wing dihedral in real-time should be accomplished with a visual display of results available to the test crew during flight
- Procedure to control wing dihedral in flight is necessary for the Helios class of vehicle

Wing Shape Sensing Background

- **Current Wing Displacement Techniques**
 - **Optical Methods (Flight Deflection Measurement System)**
 - **1980s - Highly Maneuverable Aircraft Technology (HiMAT)**
 - **2000s - F/A-18 Active Aeroelastic Wing (AAW)**
 - **Strain Gage Approaches**
- **Limitations**
 - **Current techniques utilize approaches that are too heavy and not appropriate for weight-sensitive, highly-flexible structures**

Research Objectives for Ikhana

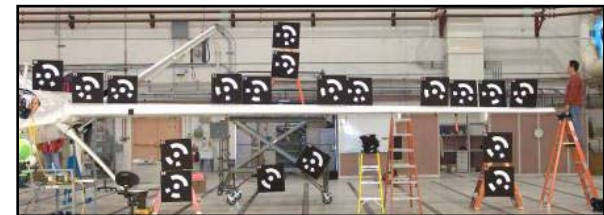
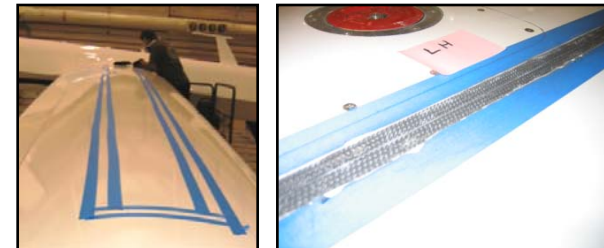
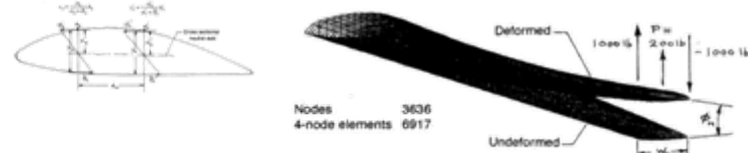
- Flight validate fiber optic sensor measurements and real-time wing shape sensing predictions on NASA's Ikhana vehicle (FY08)
- Validate fiber optic mathematical models and design tools (FY08)
- Assess technical viability and, if applicable, develop methodology and approach to incorporate wing shape measurements within the vehicle flight control system (FY08-FY09)
- Develop and flight validate advanced approaches to perform active wing shape control using
 - conventional control surfaces (FY09-FY10)
 - active material concepts (FY09-FY11+)



Research Areas

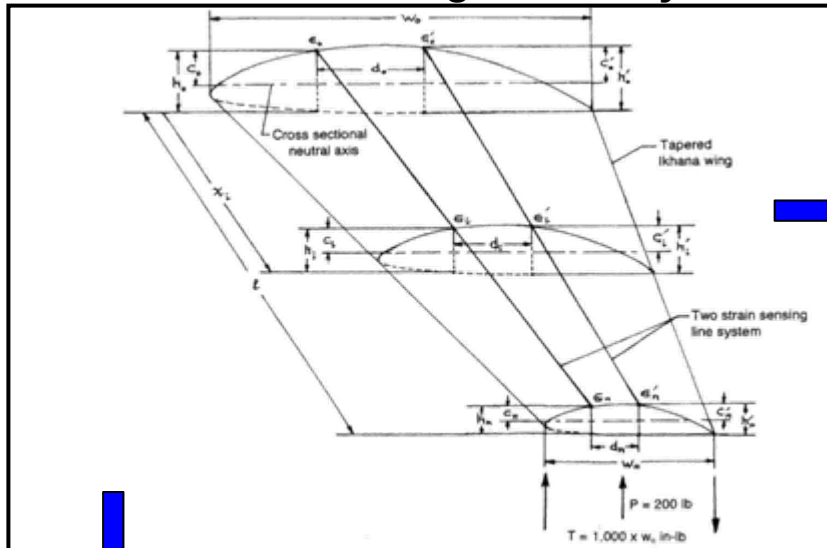
- Algorithm Development
- FBG System Development
- Instrumentation
- Ground Testing
- Flight Testing

$$y_n = \frac{\Delta l^2}{6c} \left\{ (3n-1)\varepsilon_0 + 6 \sum_{i=1}^{n-1} (n-i)\varepsilon_i + \varepsilon_n \right\}$$



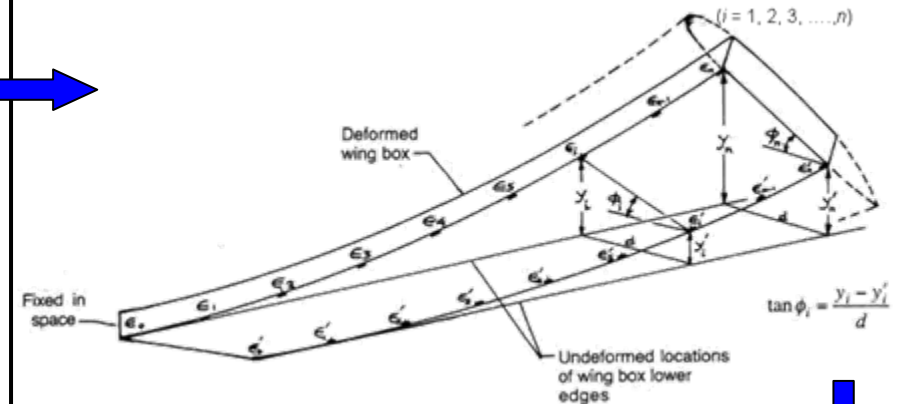
Algorithm Development (Ikhana)

Ikhana Wing Geometry

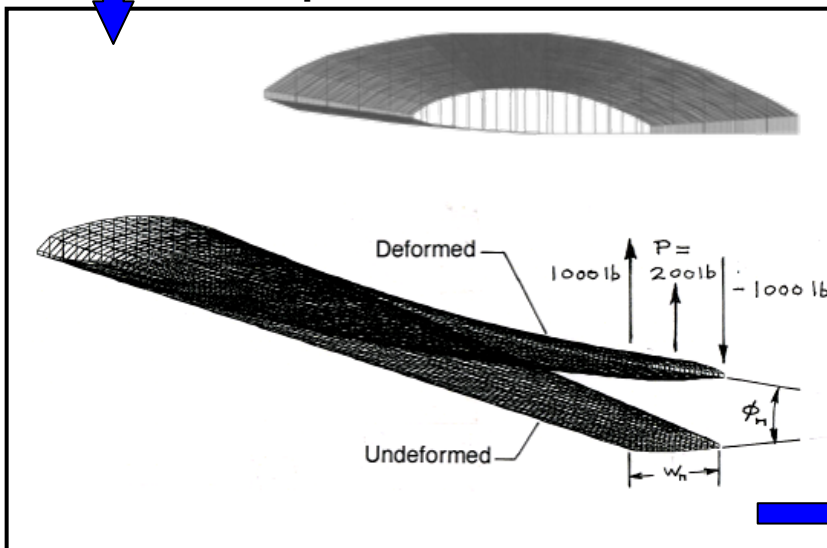


Analytical Models

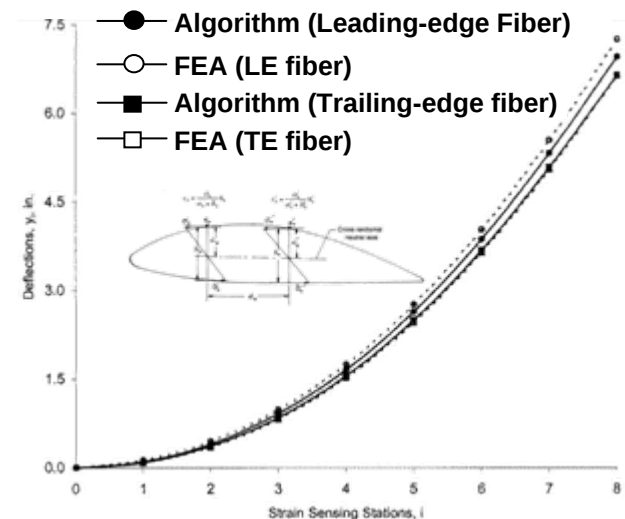
$$y_i = \frac{(\Delta t)^2}{6} \sum_{j=1}^i \frac{1}{c_{j-1}} \left\{ \left[3(2j-1) - (3j-2) \frac{c_{i-j+1}}{c_{i-j}} \right] \mathbf{E}_{j-j} + (3j-2) \mathbf{E}_{j-j+1} \right\} + \mathbf{y}_0 + i \Delta t \tan \theta_0$$



Computational Models



Analytical/Comp. Comparison



Ikhana Fiber Optic Flight System

- **Current flight system specifications**

- Fiber count 4
- Max fiber length 40 ft
- Max sensing length 20 ft
- Max sensors / fiber 480
- Total sensors / system 1920
- Sample rate 2 fibers @ 50 sps
4 fibers @ 24 sps
- Power 28VDC @ 4 Amps
- User Interface Ethernet
- Weight (non-optimized) 23 lbs
- Size (non-optimized) 7.5 x 13 x 13 in

- **Environmental qualification specifications**

- Shock 8g
- Vibration 1.1 g-peak sinusoidal curve
- Altitude 60kft at -56C for 60 min
- Temperature $-56 < T < 40\text{C}$



Fiber Optic Flight System



Ikhana Avionics Bay



Ikhana in Flight

Flight Instrumentation

- **Instrumentation**

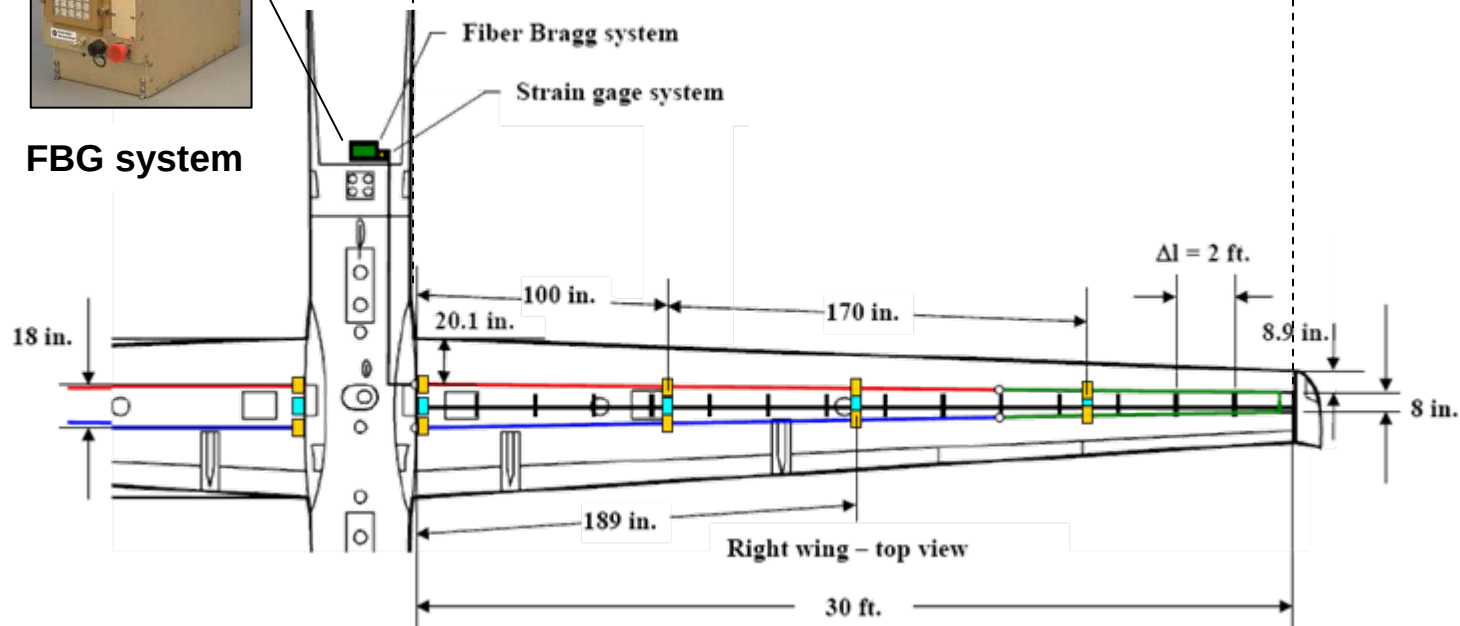
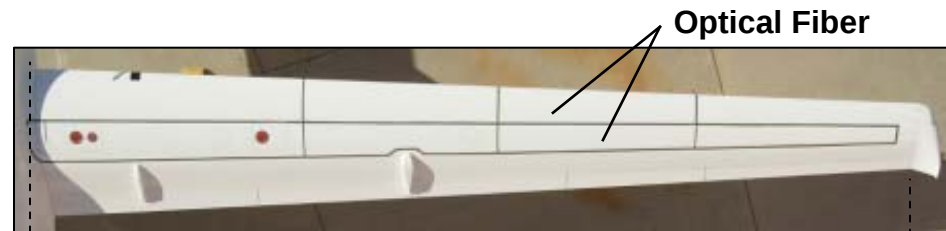
- 2880 FBG strain sensors (1920 recorded at one time)
- 1440 FBG sensors per wing
- User-selectable number of FBG sensors for real-time wing shape sensing
- 16 strain gages for FBG sensor validation
- 8 thermocouples for strain sensor error corrections



Strain gage system



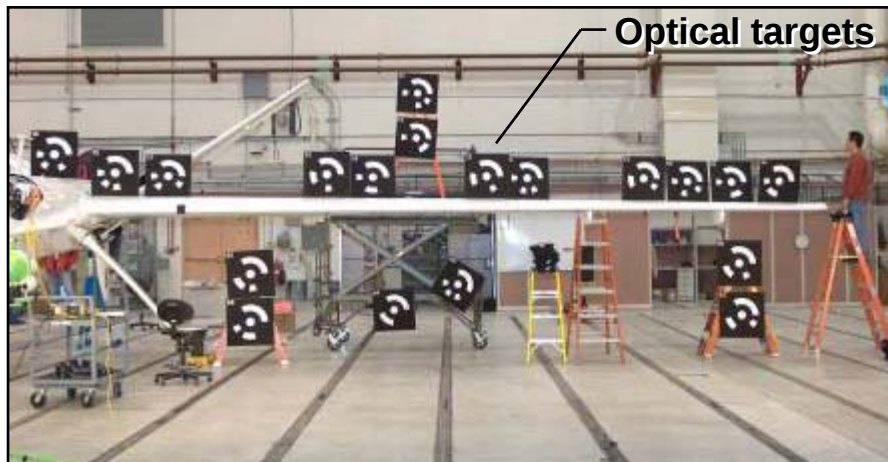
FBG system



Ground Test Validation - Ikhana

- **Ground validation testing**

- Conducted ground validation testing January 16-18, 2008
- Used Dryden's high resolution / high speed optical measurement system as validation standard
- 10 measurement stations placed on left wing (1 on center fuselage)
- Five load cases applied
- Good agreement between FOWSS and optical system



Left wing – aft view

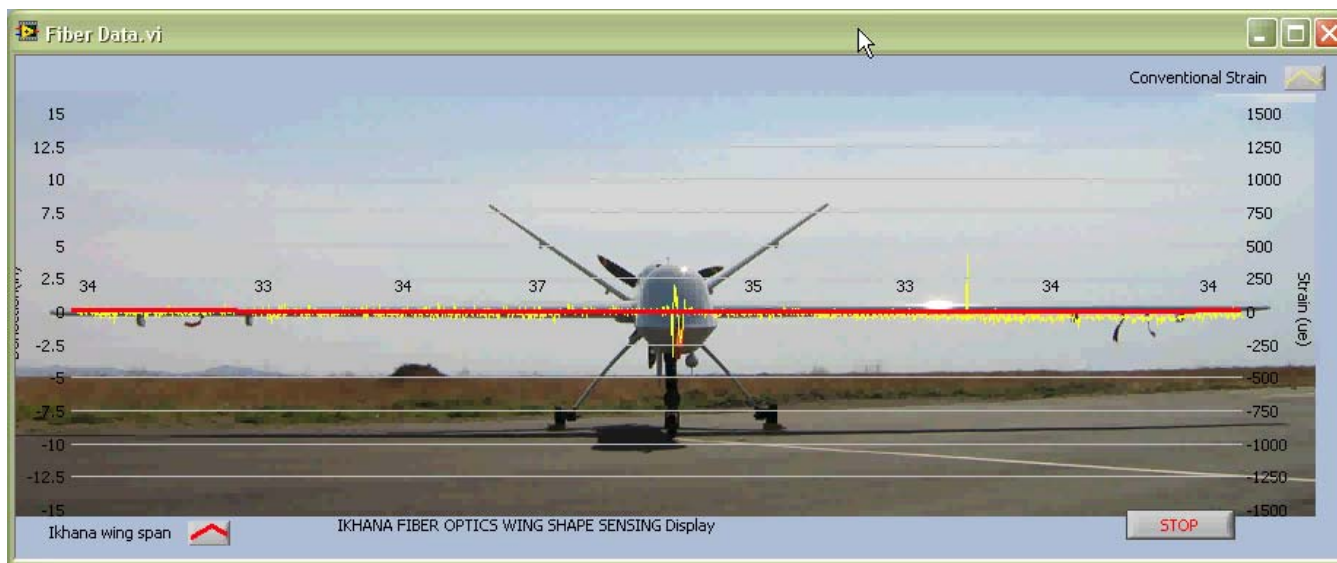


Left wing – inboard view

Flight Test Validation - Ikhana

- **Flight validation testing**

- Conducted first flight validation testing April 28, 2008
- Believed to be the first flight validation test of FBG strain and wing shape sensing
- Multiple flight maneuvers performed
- FOWSS system performed well throughout entire flight – no issues
- Data reduction and correlation on going



Video clip of flight data (from taxi to take-off) superimposed on Ikhana photograph

Concluding Remarks

- **Fiber Optic Wing Shape Sensing on Ikhana involves five major areas**
 - Algorithm development
 - Local-strain-to-displacement algorithms have been developed for complex wing shapes for real-time implementation (NASA TP-2007-214612, patent application submitted)
 - FBG system development
 - Dryden advancements to fiber optic sensing technology have increased data sampling rates to levels suitable for monitoring structures in flight (patent application submitted)
 - Instrumentation
 - 2880 FBG strain sensors have been successfully installed on the Ikhana wings
 - Ground Testing
 - Fiber optic wing shape sensing methods for high aspect ratio UAVs have been validated through extensive ground testing in Dryden's Flight Loads Laboratory
 - Flight Testing
 - Real time fiber Bragg strain measurements successfully acquired and validated in flight (4/28/2008)
 - Real-time fiber optic wing shape sensing successfully demonstrated in flight
- **Current Status**
 - Dryden FOWSS system successfully qualified for Predator-B flight environment
 - FOWSS system currently installed on Ikhana aircraft
 - Flights being conducted from April - May 2008

Backup Slides

Dryden Fiber Optic System

- **Current ground system specifications**

- Fiber count 4
- Max. fiber length 40 ft
- Max sensing length 20 ft
- Max. sensors / fiber 480
- Total sensors per system 1920
- Min. grating spacing 0.5 in
- Sample rate 2 fibers @ 50 sps
4 fibers @ 24 sps
- Interface Gigabit Ethernet
- Power 120 VAC
- Weight 12 lbs
- Size 9 x 5 x 11 in

